SVN 20 End-Of-Life Frequency Standard Test Results

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Abstract

In early 1989 the first Block II Global Positioning System (GPS) satellites were launched, marking the beginning of the second phase of the GPS program. The satellites were designed for a seven-and-one-half year lifespan and a six-year mean mission duration. Launched in March of 1990, SVN 20 was the seventh of the Block II GPS satellites. On 11 May 1996, SVN 20 was set permanently unhealthy to users after being operational for just over six years. Due to degradation of the Attitude Velocity and Control Subsystem (AVCS), SVN 20 was no longer capable of maintaining the stable, earth-pointing platform necessary to perform the GPS navigation mission. However, through intensive maintenance by personnel at the Master Control Station (MCS) at Falcon Air Force Base, it was possible to stabilize the vehicle long enough to perform extensive end-of-life testing on the four on-board atomic frequency standards. These tests on both the cesium and rubidium frequency standards varied in duration and complexity.

Of the four frequency standards, one had been operational for five months, two had been used previously but were since off-line for two years and four years, respectively, and one had never been initialized. Areas of interest for the rubidium clocks included the determination of the temperature coefficient, voltage-controlled crystal oscillator (VCXO) open-loop operations, and measurement of the C-field and VCXO tune ranges. For the cesium frequency standards, the tests focused on Ramsey pattern generation, gain determination through loop time constant measurement, and C-field and VCXO performance degradation.

All four clocks were still operational at various levels of performance and accuracy. The results of these tests were encouraging in that they supported conclusions made during the SVN 9 and SVN 10 (Block I) end-of-life testing. It is hoped these results will be useful to the GPS clock community as observations of performance characteristics of space-based atomic frequency standards.

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I. INTRODUCTION

On 11 May 1996, SVN 20 became the first Block II satellite to leave operational service. Due to problems with the vehicle's Attitude, Velocity and Control Subsystem (AVCS), the satellite could not provide a reliable, three-axis stabilized platform. Since a stable platform is essential to the navigation mission, the satellite was no longer useful as an operational asset. However, the vehicle could still provide valuable information about the performance of atomic frequency standards in a space environment.

Because of SVN 20's unusual configuration at the time of testing, there were unique challenges to overcome. With the satellite spinning about its yaw axis ($\approx$ 25 rpm) without its L-band assembly consistently fixed on the earth, the Master Control Station (MCS) could only gather approximately 1.5 hours of navigation data per 12-hour orbit. The reliability of the MCS Kalman filter state estimates normally decreases with smaller than normal amounts of data. However, Boeing and Air Force studies proved that the filter's convergence in the case of SVN 20 would have been operationally acceptable, if necessary. Additionally, the testing had to be accomplished in a limited time frame (16 September 1996 through 26 November 1996) due to other vehicle considerations. The clock tests performed were the Temperature Coefficient Determination, the Voltage-Controlled Crystal Oscillator (VCXO) Open-Loop Test, Ramsey Pattern Generation, and Loop Time Constant Determination. Additionally, Rubidium Frequency Standard (RFS) #1 was initialized for the first time, and Cesium Frequency Standard (CFS) #3 and CFS#4 were re-initialized. Many interesting results were obtained, which will prove useful to those interested in space-based frequency standard performance.

II. TEMPERATURE COEFFICIENT DETERMINATION

The effects of temperature changes play a large role in determining the final frequency stability of GPS clocks. Rubidium frequency standards are more temperature-dependent than cesiums, and this is reflected in the GPS Block II program specifications for temperature coefficient. According to these specifications, Block II cesium standards must have a temperature coefficient of less than 2 parts in 10e-13 parts per degree Celsius.[1] Rubidium standard specifications require a coefficient of less than 2 parts in 10e-12 parts per degree Celsius.[2] Because of this order of magnitude difference, rubidium standards are equipped with Active Baseplate Temperature Control Units (ABTCUs). These heaters were designed to maintain clock temperature within +/- 0.1°C on one of four commandable settings. These settings are: "A" = 26.8 °C, "B" = 29.9°C, "C" = 33.4 °C, "D" = 37.0°C.[3]

Method

The temperature coefficient of a rubidium standard can be measured by recording the MCS Kalman filter's estimate of frequency offset, in the units of s/s, at ABTCU setting "D," along with the clock's exact temperature at that point. The ABTCU is then commanded to setting "C." Once the clock's temperature stabilizes at the lower value, the Kalman filter's estimate of frequency offset is again recorded (approximately 24 hours later), along with clock temperature. This process is repeated for every lower ABTCU setting that can provide a stable temperature above the cyclic operating temperature of the rest of the payload. The standard's temperature coefficient is obtained by calculating the ratio of frequency change to temperature change. RFS#1 and RFS#2 were tested on SVN 20. By comparing the current temperature coefficients to coefficients obtained during pre-launch testing, approximately 10 years earlier, the effects of prolonged exposure to the space environment could be determined. We expected the temperature coefficients to degrade slightly over time, but not enough to create any mission impact.

Test Results

The clock temperature on RFS#1 changed from 37.26° to 34.36° when the ABTCU was commanded to setting "C" from setting "D". After approximately 72 hours, the Kalman estimate of frequency offset changed from +5.34e-12 to +1.22e-11. This change in frequency yielded a temperature coefficient of **-23.66 10e-13** Δf/f per degree Celsius. Ground testing accomplished in July 1987 measured the temperature coefficient as **-2.7 10e-13** Δf/f per degree Celsius.

RFS#2's ABTCU was commanded to setting "C" from setting "D". After approximately 12 hours of ABTCU temperature observation, the final resting temperature of RFS#2 was about 2°C higher than that of ABTCU setting "C". Because of this, the ABTCU was unable to properly regulate the clock temperature at setting "C" and MCS operators were unable to obtain temperature coefficient data on RFS#2.

Conclusions

The results of this test show the temperature coefficient of RFS#1 worsened by a factor of **8.76** from July 1987 to September 1996. It appears prolonged exposure to the space environment (over 6 years) and a period of over 3 years spent on the ground had an effect on the temperature coefficient of RFS#1. The extent of this effect on the navigation mission is directly related to the ability of the ABTCU to regulate temperature to within its designed range of ± 0.1 °C. Obviously, any degradation of the ability of the ABTCU to regulate temperature is more severe with a larger temperature coefficient. It is important operators realize ground test values of temperature coefficients will degrade over time, and should properly account for this change when analyzing clock and ABTCU performance.

III. VCXO OPEN-LOOP RUN TEST

The nominal configuration of a GPS frequency standard involves locking the VCXO to the stabilizing effects of the physics package loop. In the event the physics package becomes unstable, it may be necessary to use the VCXO in an open-loop configuration. We used this test to determine the feasibility of operating in the open-loop configuration. We expected the open-loop configuration would not prove to be acceptable for operations due to very large ranging errors and inconsistent run-offs.

Method

In separate tests, RFS#1 and RFS#2 were commanded into the open atomic loop configuration, disconnecting the VCXO from the rubidium physics package. The VCXOs were then tuned to a nominal value and the satellite's ranging errors were observed, once every 15-minute K-point, for several visibility periods. These measurements informed MCS operators of the consistency and magnitude of the open loop run-off.

Test Results

Tables 1, 2, and 3 show the ranging errors recorded with RFS#1, RFS#2, and CFS#3 in an open-loop configuration.

Conclusions

The rates of run-off for all three open-loop tests seem to be fairly consistent from visibility period to visibility period. These run-off rates are directly related to how accurately MCS operators could tune each VCXO after opening the loop. It is clear the average frequency residuals for RFS#2 & CFS#3 were orders of magnitude smaller than that of RFS#1. This is because RFS#1 was tuned to 50% and RFS#2 and CFS#3 were tuned to match their loop control voltages with their previous closed-loop values. Even the most accurately tuned VCXO achieved an average frequency residual of 4.9 e-10 s/s. This is more than an order of magnitude larger than a normal closed-loop clock.

Due to the large magnitude of the ranging errors and timing discrepancies, it is unrealistic to expect a standard to operate in the open-loop configuration without abnormal MCS intervention. The necessary Kalman maintenance, frequent uploads, and timing adjusts would burden the operations crews to a more than acceptable level.

IV. RAMSEY PATTERN GENERATION

The Ramsey pattern of a GPS cesium frequency standard shows the condition of the beam tube, such as where the center and side lobe frequencies of the standard are located with respect to the clock's VCXO tuning range. It also provides insight into the gain of the tube and the symmetry of the RF inserted into the tube. Based on SVN 10's end-of-life test results, it was expected the Ramsey patterns of SVN 20's cesium standards would show some degradation over time.[4]

Method

An operational frequency standard normally operates with the atomic loop closed and the center frequency located somewhere near the VCXO's 50% tune value. It is possible to plot the Ramsey pattern of a GPS cesium frequency standard by opening the atomic loop and commanding the VCXO to incremental tune values. In this case, increments of 5 and 10% were used. At each tuning value, the beam current (proportional to the gain of the system) is recorded and plotted versus the tune percentage. The resulting plot shows peaks and valleys, with the peaks being either the center or side lobe frequencies.

Test Results

Once the beam current is plotted versus the VCXO tune percentage, one can see where the center frequency may lie, depending on how much the VCXO has aged. Data for CFS#3 from 6 Aug 94 and 7 Nov 96areshown in Figures A and B. Data for CFS#4 from 21 Nov 96areseen in Figure C.

Conclusions

The data indicate the Ramsey pattern of SVN 20's cesium standards degraded with age. When comparing the Ramsey pattern of CFS#3 recorded in 1994 with that recorded in 1996, one can see,as the gain of the system degraded, the definition of the Ramsey pattern also degraded. This could be a contributing factor to the instability of CFS#3 when it was deactivated in 1994. When observing the Ramsey pattern of CFS#4, it is apparent the side lobes are not clearly defined. This may be due to the gain of this standard degrading and the noise level increasing. It also indicates that frequency standards degrade in space even when not powered on. Because there are no pre-launch Ramsey patterns to compare our results with, it is unclear exactly how much CFS#4's Ramsey pattern changed over time.

V. LOOP TIME CONSTANT DETERMINATION

The atomic loop of a cesium standard detects a change in the frequency of the VCXO and makes appropriate changes to return the frequency to its nominal value. The correction for any given frequency change takes a greater amount of time as the frequency standard ages. This amount of time is known as the loop time constant (LTC). An average value of LTC for a new cesium standard is about 10-15 seconds. It was expected the LTCs of SVN 20's standards would show some degradation over time, because the LTC is a function of the gain of the system. This test was devised to determine to what extent the LTCs of SVN 20's cesium clocks have degraded with age.

Method

It is possible to determine the LTC of a cesium frequency standard by commanding the VCXO to a value about 4% (or 0.2 Hz) greater than its nominal tune and recording the time the close loop command was accepted. At this point the VCXO will begin correcting for the induced frequency change. The time it takes for the VCXO to recover 63% of the induced frequency error is the LTC. This process can also be repeated for a tune value about 4% lower than the VCXO's nominal tune value to observe the symmetry of the Ramsey pattern.

Test Results

CFS#3 LTC when moved up in frequency about 4%:	142 seconds
CFS#3 LTC when moved down in frequency about 4%:	127 seconds
CFS#4 LTC when moved up in frequency about 4%:	104 seconds
CFS#4 LTC when moved down in frequency about 4%:	80 seconds

Conclusions

Six years of exposure to the space environment affected the LTCs of SVN 20's cesium standards. CFS#3's LTC degraded (equivalent to a loss of gain) by a factor of 9 and CFS#4's LTC degraded by a factor of 6. A large degradation factor was expected for CFS#3 because it was powered on for over 4 years. CFS#4 showed a rather large degradation factor for being powered on for only 4 months. It should be noted that both cesium standards started out with the same beam current value of 18 nanoamperes. It is apparent time spent on the ground and in space degrades the LTC of cesium standards, even when not powered on. This may be a consideration when determining which clock to swap to (Rb vs. Cs) in future operational situations.

VI. NEW CLOCK INITIALIZATION (RFS#1)

Due to the low reliability of atomic frequency standards (0.64 for cesium and .76 for rubidium) with respect to other satellite components, each GPS satellite carries four atomic clocks into orbit. When an operational clock fails, a standby clock is powered up and brought on line. SVN 20 was launched in March of 1990. The first clock, CFS#3, operated for more than 4 years and was turned off in August 1994. RFS#2 was subsequently powered up and was in operation until January 1996. CFS#4 was then turned on and remained in service until the end of SVN20's operational lifetime due to AVCS problems in May 1996. RFS#1 was never powered on during SVN 20's operational lifetime. This test was designed to initialize RFS#1 after over 6 years of cold storage in orbit. Because of the harsh space environment, there was a definite chance the standby clock would not function properly after so many years of cold storage (~10°C). Based on previous end-of-life test results,it was expected SVN 20's RFS#1 would power on nominally and perform at nominal operational levels.[4,5]

Method

The test followed standard clock initialization procedures. The new clock was powered up and allowed to stabilize (approximately a two-hour process). A C-field tune was accomplished to minimize the frequency offset. As soon as the C-field tune was complete, SVN 20 was provided with a routine navigation upload. Since it was unhealthy, the vehicle was usually uploaded once a day regardless of the size of the ranging errors. NRL observed the clock's one-day stability through the use of the Hadamard deviation.

Test Results

The performance characteristics test of RFS#1 started on 22 July 1996 and lasted until 26 September 1996. The clock was powered up on 1 July 1996. The tests recorded Kalman data as the clock warmed up. The Kalman estimate of the A_1 (frequency offset) state at the end of the test is shown in Table 4. Also shown is the NRL estimates of the clock stability based on the Hadamard deviation.

Conclusions

RFS#1 behaved normally for a newly initialized Block II Rubidium standard. Its clock frequency state estimate was certainly within operational limits. In the realm of stability, RFS#1 met one-day stability program specifications (5.0 e-13) and was easily acceptable for operational use.[2] Based on drift plots for the last three days of the characteristics observation, it was observed that RFS#1 had assumed a negative drift rate. This is expected of a nominally performing rubidium frequency standard after 2 to 3 months of activation.

The results of this test are encouraging. Based on the performance of RFS#1 after over 6 years of cold storage, it seems this clock would have behaved acceptably were it necessary to utilize it as an operational asset. This bodes well for the chances of other clocks in the constellation which have been stored for similar periods of time.

VII. OLD CLOCK RE-INITIALIZATION (RFS#2, CFS#3)

This test was designed to re-initialize RFS#2 and CFS#3 after being deactivated on 16 Jan 96 and 6 Aug 94, respectively. Upon re-initialization, each clock's performance characteristics were recorded and analyzed. Our expectation was that RFS#2 would perform relatively well. It was deactivated due to suspect performance, with these end-of-life data points providing some additional insight into its instability when deactivated in Jan 1996. We expected CFS#3 to perform at a less than adequate level. It was in operation for over 4 years, and its gain (beam current) was relatively low when deactivated.

Method

Clock stability was recorded by Naval Research Laboratory (NRL), and the MCS Kalman filter estimated clock states.

Test Results

RFS#2 was powered back up on 17 October 96. Data were received from 17 October 96 - 4 November 96. Table 5 describes RFS#2's performance characteristics during that time period. The one-day stability data were obtained from Naval Research Laboratory's (NRL) Navstar Analysis Update No. 20-12. The clock state estimates were obtained from the MCS Kalman filter. CFS#3 was powered back up on 6 November 96. Data were received from 8 November 96 - 20 November 96. Table 6 describes CFS#3's performance characteristics during that time period. The clock state estimates were obtained from the MCS Kalman filter.

Conclusions

The results obtained from observing RFS#2 did not produce any discouraging conclusions. RFS#2's Kalman clock states were all within operational limits, and looked very normal for a rubidium frequency standard that had been earlier labeled "suspect". Its one-day stability was well within the system specification of 5 e-13.[2] CFS#3's clock states were nominal for the short period of time they were monitored by the MCS. It is expected that its stability, however, would have been questionable due to its low beam current (gain) value of about 1.6 na.

VIII. CONCLUSION

Despite its unique configuration and other obstacles, a great deal was learned from SVN 20's end-of-life frequency standard testing. One of the greatest benefits was confirmation of test results obtained from SVN 9 and SVN 10 during their end-of-life testing. Even with the Block IIR satellites entering the constellation, the Block II/IIA constellation will remain the majority for many years. Information gained from these types of tests will help the MCS operators sustain the aging constellation more effectively and ensure continued support to navigation and time-transfer users worldwide well into the 21st century.

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[1] *"Cesium Standard Procurement Specification,"* MC474-0031, Rev. A, Sec. 05, 26 October 1981 (Rockwell International, Inc.).

[2] *"Rubidium Standard Procurement Specification,"* MC474-0030, Rev. F, Sec. 05, 5 May 1988 (Rockwell International, Inc.).

[3] *"Block II GPS Orbital Operations Handbook,"* Vol. I, Sec. 2.6, *"Thermal Control Subsystem Description."*

[4] G.L Dieter and M.J. Van Melle 1996, *"The End of an Era: SVN 10 End-Of-Life Frequency Standard Testing,"* Proceedings of the 28th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1996, Reston, Virginia, USA, pp. 429-439.

[5] G.E. Hatten 1995, *"SVN 9 End-Of-Life Testing,"* Proceedings of the 26th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 6-8 December 1994, Reston, Virginia, USA (NASA CP-3302), pp. 405-414.

XI. TABLES & FIGURES

2 Oct 96/1253z	Atomic Loop Opened & VCXO tuned to 50%.		
Time	SV Clock Bias (s)	Ranging Error (m)	
2 Oct 96/2330z	3.05581401e-3	-916121	
3 Oct 96/0000z	3.19976221e-3	-959276	
average run-off 2 Oct 96/2330z - 3 Oct 96/0000z:			21577 meters/15 minutes
3 Oct 96/1045z	6.29589865e-3	-1887486	
3 Oct 96/1100z	6.36795353e-3	-1909088	
3 Oct 96/1115z	6.43995129e-3	-1930673	
3 Oct 96/1130z	6.51195057e-3	-1952258	
3 Oct 96/1145z	6.58394624e-3	-1973842	
3 Oct 96/1200z	6.65594929e-3	-1995427	
average run-off 3 Oct 96/1045z - 3 Oct 96/1200z:			21588 meters/15 minutes
RFS#1 Average Frequency Residual:		8.0 e-8 s/s	

Table 1. RFS#1 Open Loop Data.

7 Nov 96/1548z	Atomic Loop Opened & VCXO tuned so that loop control voltage would match where it was when the clock was at GPS frequency.	
Time	SV Clock Bias (s)	Ranging Error (m)
7 Nov 96/2015z	4.52181102e-5	-13556
7 Nov 96/2030z	4.73212038e-5	-14187
7 Nov 96/2045z	4.95378854e-5	-14851
7 Nov 96/2100z	5.16745958e-5	-15492
average run-off 310/2015 - 310/2100:		645 meters/15 minutes
8 Nov 96/0815z	1.46054578e-4	-43787
8 Nov 96/0830z	1.48107409e-4	-44402
8 Nov 96/0845z	1.50157346e-4	-45017
8 Nov 96/0900z	1.52200032e-4	-45629
8 Nov 96/0915z	1.54237559e-4	-46240
8 Nov 96/0930z	1.56278328e-4	-46852
average run-off 311/0815 - 311/0930:		613 meters/15 minutes
RFS#2 Average Frequency Residual:		2.3 e-9 s/s

Table 2. RFS#2 Open Loop Data.

20 Nov 96/1939z	Atomic Loop Opened & VCXO tuned so that loop control voltage would match where it was when the clock was at GPS frequency.	
Time	**SV Clock Bias (s)**	**Ranging Error (m)**
20 Nov 96/2045z	2.61563055e-6	-784
20 Nov 96/2100z	2.13284330e-6	-639
average run-off 20 Nov 96/2045z - 20 Nov 96/2100z:		145 meters/15 minutes
21 Nov 96/0745z	-1.85124471e-5	5550
21 Nov 96/0800z	-1.89520962e-5	5681
21 Nov 96/0815z	-1.94207469e-5	5822
21 Nov 96/0830z	-1.98724160e-5	5958
21 Nov 96/0845z	-2.03418410e-5	6098
average run-off 21 Nov 96/0745z - 21 Nov 96/0845z:		137 meters/15 minutes
21 Nov 96/1930z	-3.95204347e-5	11848
21 Nov 96/1945z	-3.99226219e-5	11969
21 Nov 96/2000z	-4.03524382e-5	12098
21 Nov 96/2015z	-4.07672579e-5	12222
21 Nov 96/2030z	-4.13194989e-5	12387
21 Nov 96/2045z	-4.16899654e-5	12498
21 Nov 96/2100z	-4.21059977e-5	12623
average run-off 21 Nov 96/1930z - 21 Nov 96/2100z:		129 meters/15 minutes
22 Nov 96/0730z	-5.94009503e-5	17808
22 Nov 96/0745z	-5.97828011e-5	17923
22 Nov 96/0800z	-6.01886173e-5	18044
22 Nov 96/0815z	-6.05825976e-5	18162
22 Nov 96/0830z	-6.09610576e-5	18276
22 Nov 96/0845z	-6.13661593e-5	18397
average run-off 22 Nov 96/0730z - 22 Nov 96/0845z:		118 meters/15 minutes
CFS#3 average frequency residual:	4.9 e-10 s/s	

Table 3. CFS#3 Open Loop Data.

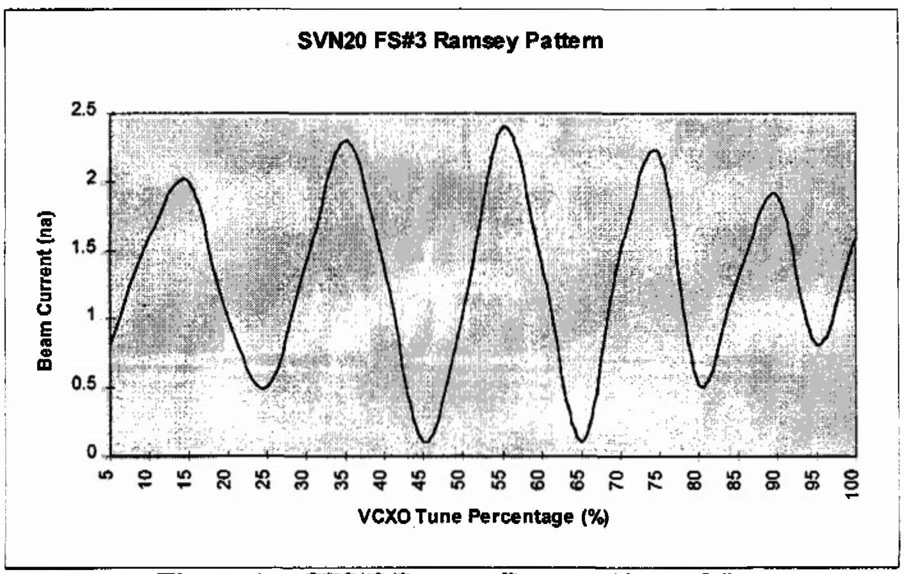

Figure A. CFS#3 Ramsey Pattern (6 Aug 94).

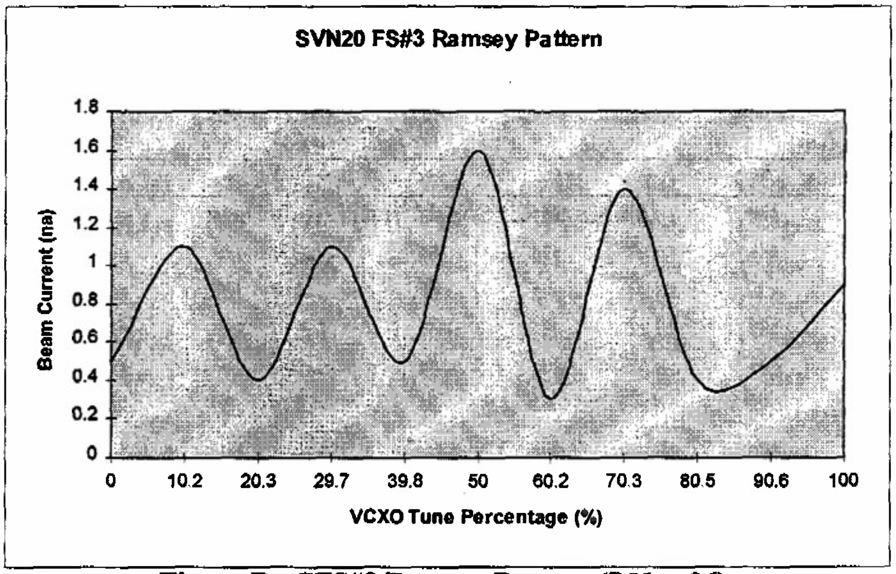

Figure B. CFS#3 Ramsey Pattern (7 Nov 96).

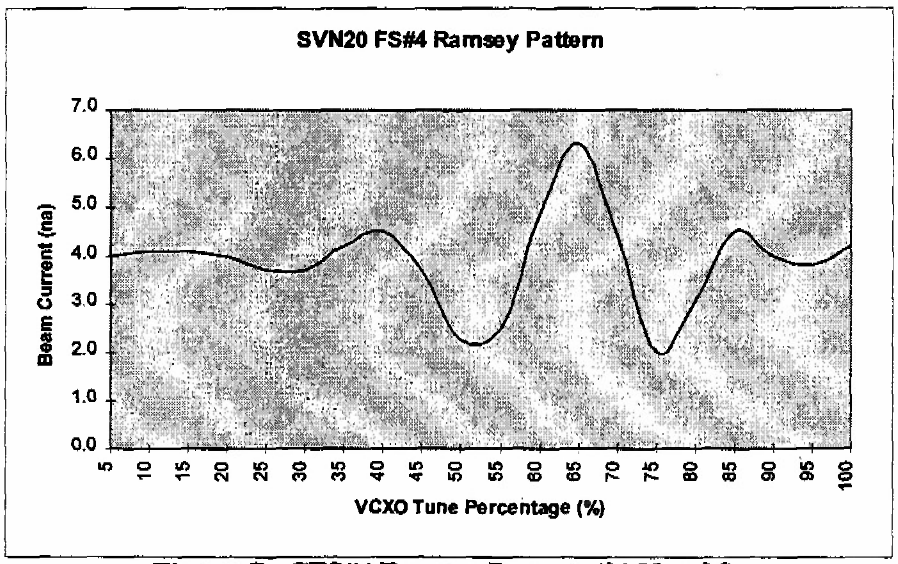

Figure C. CFS#4 Ramsey Pattern (21 Nov 96).

Clock State	FS #1
Clock Frequency (A_1)	5.34 e-12 (s/s)
Stability (τ = one-day) (data from NRL)	1.5 e-13 (Hadamard Deviation)

Table 4. RFS#1 Initialization Data.

Clock State	FS #2
Clock Phase (A_0)	-2.60 e-5 (s)
Clock Frequency (A_1)	-1.76 e-11 (s/s)
Clock Frequency Drift (A_2)	-3.32 e-18 (s/s^2)
Stability (τ = one day) (data from NRL)	1.9 e-13 (aging correction = 1.3 e-13 per day)

Table 5. RFS#2 Initialization Data.

Clock State	FS #3
Clock Phase (A_0)	7.73 e-5 (s)
Clock Frequency (A_1)	-4.54 e-13 (s/s)

Table 6. CFS#3 Initialization Data.